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RESEARCH PAPER

Seasonal dynamics of gas regulation service in forest ecosystem

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Abstract: Using the 3-year observational data from ChinaFlux (Chinese Terrestrial Ecosystem Flux Research Network), we studied the gas regulation flux dynamics and cumulative process of gas regulation value in Qianyanzhou middle subtropical plantation (QYF) and Changbai Mountain temperate mixed forest (CBF). The gas regulation service was differentiated into vegetation gas regulation service and net ecosystem gas regulation service. Carbon tax approach, reforestation cost approach and industrial oxygen approach were employed to calculate gas regulation value. Results show that there was significant seasonal variation in vegetation gas regulation flux. Daily CO_2 uptake fluxes averaged 82.00 $kg·ha^{-1}·d^{-1}$ and 59.37 $kg·ha^{-1}·d^{-1}$ and the corresponding O_2 emission fluxes were 59.65 $kg·ha^{-1}·d^{-1}$ and 43.19 $kg·ha^{-1}·d^{-1}$ for QYF and CBF, respectively. The cumulative curves of vegetation gas regulation value always followed a sigmoid shape, and the annual gas regulation value produced by vegetation was RMB 14 342.69 $yuan·ha^{-1}$ and RMB 10 384.18 $yuan·ha^{-1}$ for both QYF and CBF, respectively. In terms of monthly net ecosystem gas regulation service, QYF appeared as a CO_2 sink and O_2 source for the whole year, while CBF appeared to be a CO_2 sink and O_2 source mainly in the period between May and September. The cumulative curves of net ecosystem gas regulation value presented a sigmoid ("S") shape for QYF, while a unimodal type curve for CBF. The annual net ecosystem gas regulation value was 8470.52 $yuan·ha^{-1}$ and 5091.98 $yuan·ha^{-1}$ for QYF and CBF, respectively. The economic value of both the vegetation gas regulation service and net ecosystem gas regulation service were mainly produced between May and October.

Keywords: gas regulation service; flux; cumulative; CO_2 uptake; O_2 emission

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Introduction

As the main body of global terrestrial ecosystem, forest ecosystem produces important ecosystem services (Costanza et al. 1997; Myers 1997). In forest ecosystem, plants transform solar energy into biotic energy through photosynthesis, fixing CO_2 and releasing O_2, which plays an irreplaceable role in maintaining the CO_2/O_2 balance and mitigating greenhouse gases emissions. Annually, two thirds of the global terrestrial carbon sequestration is achieved by forest ecosystem (Kramer 1981). Costanza et al. (1997) grouped the ecosystem services into 17 major categories for 16 biomes, in which gas regulation service is the most important one. According to the equivalent weight factor of ecosystem services per hectare of forest ecosystem in China, gas regulation service was given the high equivalent factor of 3.5, which is the second largest ecosystem service delivered by forest (Xie et al. 2003). The economic value of carbon fixation and O_2 emission was estimated at RMB 1626.76×10^8 $yuan·ha^{-1}·a^{-1}$ and 6732.48×10^8 $yuan·ha^{-1}·a^{-1}$ for China forest ecosystem (Zhao et al. 2004). A number of other studies also evaluated gas regulation services at the country and regional level (Ouyang et al. 2004; Jin et al. 2005; Yu et al. 2005a; Yu et al. 2005b).

However, to date, studies on gas regulation service of forest were mainly based on biomass and productivity survey, or forest inventory (Zhao et al. 2004; Jin et al. 2005; Yu et al. 2005b). Hence, these studies on gas regulation service were confined to evaluating and analyzing variation of gas regulation service among different forest ecosystems at the annual or interannual scale, which resulted in deficiency of the revelation of seasonal dynamics of gas regulation service. In fact, forest ecosystem is a dynamic system, and the gas regulation service also presents seasonal variation. Therefore, a study on seasonal dynamics of gas regulation service contributes to revealing the formation mechanism of gas regulation service and its process. Moreover, what the previous study evaluated is virtually vegetation gas regulation service (Zhao et al. 2004; Jin et al. 2005; Yu et al. 2005b), which overlooked heterotrophic respiration and resulted in overestimation of ecosystem gas regulation service .

In this paper, we differentiated the gas regulation service into vegetation gas regulation service and net ecosystem gas regula-

tion service, and the former was computed based on NPP (net primary productivity), while the latter was calculated based on NEP (net ecosystem productivity). Eddy covariance system can continuously and directly measure the CO_2 flux between vegetation and atmosphere, which meet the demand for study of seasonal dynamics of these two gas regulation services. The questions addressed here were: (1) characteristics of the gas regulation flux dynamics; (2) cumulative process of economic value of gas regulation service.

Materials and methods

Site description

The flux measurements were made above the plantations in Qianyanzhou Experimental Station (QYF) and broad-leaved mixed forest in Research Station of Changbai Mountain Forest Ecosystems (CBF). General situation of these two sites was listed in Table 1. More detailed descriptions of the two sites are provided by Zhang et al. (2006a), Liu et al. (2006) and Zhang et al. (2006b). The equipment in these two stations is uniform open-path eddy covariance system, and the description of the flux observation tower can be referred to the ChinaFlux website: http://www.chinaflux.org.

Data acquisition and processing

NEE (Net ecosystem carbon exchange), Re (Ecosystem respiration) and GEE (Gross ecosystem carbon exchange) flux at daily scale were provided by Chinese Terrestrial Ecosystem Flux Observational Research Network (ChinaFlux).

Table 1. General situation of the study sites

Site	Geographic location	Climate	Annual mean temperature (℃)	Annual precipitation (mm)	Crown height (m)	Dominant species	Soil type	Observational height (m)
QYF	26°44′N, 115°03′E	Subtropical monsoon climate	17.9	1542.4	11	*Pinus massonian*, *Pinus elliottii*, *Cunninghamia Lanceolata*	Red soil	39
CBF	41°29′N, 128°05′N	Temperate continental climate	3.6	713	26	*Pinus koraiensis*, *Tilia tuan*, *Quercus mongolicus*, *Fraxinus mandshurica*	Dark brown forest soil	40

Notes: QYF---Qianyanzhou middle subtropical plantation, CBF---Changbai Mountain temperate mixed forest.

The measurements were made in 2005, 2006 and 2007. Net ecosystem carbon exchange between forest and atmosphere （F_{NEE}） was computed according to the following equation：

$$F_{NEE} = \int_0^{Zr} \frac{\partial \bar{c}}{\partial t} dz + (\overline{w'c'})r \quad (1)$$

where, the first term on the equation is the storage term (F_s), the second term is the eddy CO_2 eddy flux (F_c) measured at height Z_r. Subscript r denotes a quantity at eddy flux measurement height Z_r. F_{NEE} is decomposed into F_{Re} (flux of ecosystem respiration) and F_{GEE} (flux of gross ecosystem carbon exchange) according to the following equation:

$$F_{GEE} = F_{NEE} - F_{Re} \quad (2)$$

More detailed data processing are referred to Zhang et al. (2006a), Zhang et al. (2006b). The non-linear regression technique is used as gap-filling method.

Based on flux data, CO_2 uptake and O_2 emission fluxes were computed according to the formula of photosynthesis and respiration (Guo et al. 2001; Xiao et al. 2005b):

$$6nCO_2+6nH_2O \rightarrow nC_6H_{12}O_6+6nO_2 \rightarrow nC_6H_{10}O_5$$

When 1-g carbon was sequestered, the 3.67-g CO_2 is fixed and 2.67-g O_2 is released. On ecosystem scale, GPP (Gross primary productivity) is the modulus of GEE. And GPP minus plant respiration equals NPP. Assuming the ratio of NPP/GPP (the carbon use efficiency) kept unchanged in the year, the flux of CO_2 uptake and O_2 emission by vegetation could be determined by the equation as follows:

$$A_C = -F_{GEE} \times f \times 3.67 \times 10 \quad (3)$$

$$A_O = -F_{GEE} \times f \times 2.67 \times 10 \quad (4)$$

where, A_C is the CO_2 uptake flux by vegetation (kg·ha^{-1}·d^{-1}), A_O is the O_2 emission flux by vegetation (kg·ha^{-1}·d^{-1}), F_{GEE} is the flux of gross ecosystem carbon exchange (gC·m^{-2}·d^{-1}), f is the carbon use efficiency, and 10 is a conversion factor for gC·m^{-2} to kg·ha^{-1}. The carbon use efficiency for QYF and CBF was determined by referring to literatures (Ma et al. 2008; Wang et al. 2006; Zhang et al. 2008).

NPP quantifies the carbon uptake only by plants, while NEP (negative NEE) includes carbon absorption by plants and carbon release by soils. Properly speaking, NEP is net carbon exchange between the ecosystem and the atmosphere. Therefore, the gas regulation service by ecosystem should be determined by NPP rather than NPP, and it was called net ecosystem gas regulation service in this paper. Net ecosystem gas regulation service was defined as the following equations:

$$N_C = -F_{NEE} \times 3.67 \times 10 \quad (5)$$

$$N_O = -F_{\mathrm{NEE}} \times 2.67 \times 10 \qquad (6)$$

where, N_C is the net ecosystem CO_2 uptake flux ($kg \cdot ha^{-1} \cdot d^{-1}$), N_O is the net ecosystem O_2 emission flux ($kg \cdot ha^{-1} \cdot d^{-1}$), F_{NEE} is the flux of net ecosystem carbon exchange ($gC \cdot m^{-2} \cdot d^{-1}$), and 10 is a conversion factor for $gC \cdot m^{-2}$ to $kg \cdot ha^{-1}$.

The economic value of CO_2 uptake was estimated by the average value of the cost of afforestation and Swedish carbon tax (Ouyang et al. 1999; Xiao et al. 2005a), i.e. RMB 0.20535 yuan·$kg^{-1}CO_2$. The economic value of O_2 emission was evaluated using the average value of the price of industrial O_2 (0.4 yuan·kg^{-1}) and the cost of afforestation (RMB 0.3529 yuan·kg^{-1}) in China (Ouyang et al. 1999; Xiao et al. 2005a), i.e. 0.37645 yuan·$kg^{-1}O_2$.

The cumulative economic value of gas regulation service was calculated as follows:

$$A_i = \sum_{-1}^{12} v_i \qquad (7)$$

where, A_i represents the cumulative value of gas regulation service for i months, and V_i represents the economic value of gas regulation service in ith month. In the paper, the economic value of CO_2 uptake and O_2 emission was calculated separately.

Results and discussion

Vegetation gas regulation service

Over the 3 years, the NPP were (815.50±55.18) $gC \cdot m^{-2} \cdot a^{-1}$ and (590.43±25.50) $gC \cdot m^{-2} \cdot a^{-1}$ for QYF and CBF, respectively. These results agree well with the earlier studies (Ma et al. 2008; Wang et al. 2006; Zhang et al. 2008). Ma et al. (2008) found that NPP simulated by BGC model ranged from 343.31 $gC \cdot m^{-2} \cdot a^{-1}$ to 906.42 $gC \cdot m^{-2} \cdot a^{-1}$ across twenty-one years for QYF. As to CBF, the NPP value was also consistent with results of Zhang et al. (2008) and Wang et al. (2006). Due to the seasonal variation of NPP, vegetation gas regulation service showed obvious seasonal dynamics. The seasonal variation of vegetation gas regulation service for both QYF and CBF were unimodal distribution (Fig. 1). The 3-year average daily CO_2 flux of QYF and CBF is (82.00±5.55) $kg \cdot ha^{-1} \cdot d^{-1}$ and (59.37±2.57) $kg \cdot hm^{-2} \cdot d^{-1}$, respectively. Correspondingly, the daily average O_2 flux was (59.65±4.04) $kg \cdot hm^{-2} \cdot d^{-1}$and (43.19±1.86) $kg \cdot ha^{-1} \cdot d^{-1}$, respectively. From January to April, CO_2 fluxes of both QYF and QBF were lower than their daily average CO_2 fluxes, which should be attributed to the lower temperature in environment and lower growth rate of vegetation. The peak value of CO_2 uptake flux and O_2 emission flux of QYF occurred in August, while CBF in July, which may be ascribed to the climate characteristics difference.

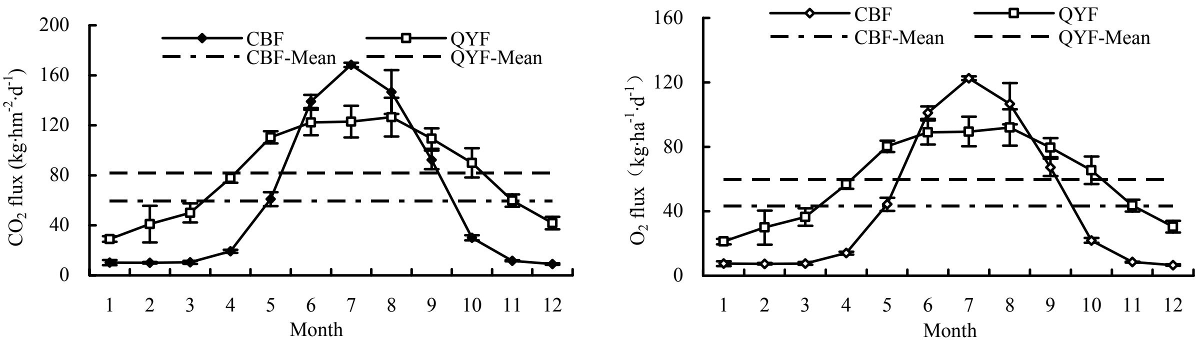

Fig. 1 Flux of CO_2 uptake (a) and O_2 emission (b) by vegetation

CBF---- Changbai Mountain temperate mixed forest; QYF---- Qianyanzhou middle subtropical plantation.

With the biomass formation, the economic value of vegetation gas regulation service is produced and accumulated. The cumulative dynamic curves of vegetation gas regulation value showed a sigmoid shape for QYF and CBF, and the annual gas regulation value produced by vegetation was (14342.69±970.54) yuan·ha^{-1} and (10384.18±448.51) yuan·ha^{-1}, respectively (Fig. 2). In our study, annual economic value of CO_2 uptake averaged 6145.91 yuan·ha^{-1} and 4449.67 yuan·ha^{-1} for QYF and CBF, respectively. These results are similar to that of Ouyang et al.(2004), who found that the economic value of CO_2 uptake for tropical monsoon forest was 5343.3 yuan·ha^{-1}. The value accumulated in spring, summer, autumn and winter accounted for 16.83%, 36.44%, 33.39% and 13.34% of the annual total value for QYF, respectively. However, the value accumulated in summer and autumn occupied 52.07% and 38.07% of the annual total value for CBF, respectively. Additionally, the vegetation gas regulation service mainly occurred between May and October, and the economic value produced during this period took up 69.83% and 90.14% of the annual total value for QYF and CBF, respectively. Besides, the monthly vegetation gas regulation value of QYF was always larger than that of CBF.

Net ecosystem gas regulation service

For the whole forest ecosystem, net ecosystem gas regulation service equals to vegetation gas regulation service subtracted by

heterotrophic respiration. The 3-year average NEP was (481.62±54.38) gC·m^{-2}·a^{-1} and (289.52±41.97) gC·m^{-2}·a^{-1} for QYF and CBF, respectively, and the results are consistent with Zhang et al. (2006a). Moreover, there were significant seasonal trend in the fluxes of CO_2 uptake and O_2 emission for both QYF and CBF (Fig. 3). At the monthly scale, QYF served as CO_2 sink and O_2 source for a whole year, and similar results were also reported in other studies (Liu et al. 2005; Zhang et al. 2006a). CBF served as a CO_2 sink and O_2 source mainly in the period between May and September, while in other months CBF maintained rough CO_2 balance or acted as a weak CO_2 source. Daily average CO_2 fluxes for QYF and CBF were 48.43 kg·ha^{-1}·d^{-1} and 29.11 kg·ha^{-1}·d^{-1}, respectively, and daily average O_2 fluxes were 35.23 kg·ha^{-1}·d^{-1} and 21.18 kg·ha^{-1}·d^{-1} for QYF and CBF, respectively. The largest net ecosystem CO_2 uptake flux and O_2 emission flux for both QYF and CBF occurred in July, and the largest net ecosystem gas regulation flux of CBF was 1.73 times as large as that of QYF. Liu et al. (2005) observed that the highest NEE (negative NEP) occurred in May or June, which differ from our results. It was attributed to severe drought in QYF in 2003. Gu et al. (2008) also demonstrated that drought affect the NEP. Additionally, the seasonal variation of CO_2 uptake flux and O_2 emission flux is greater than that of CBF.

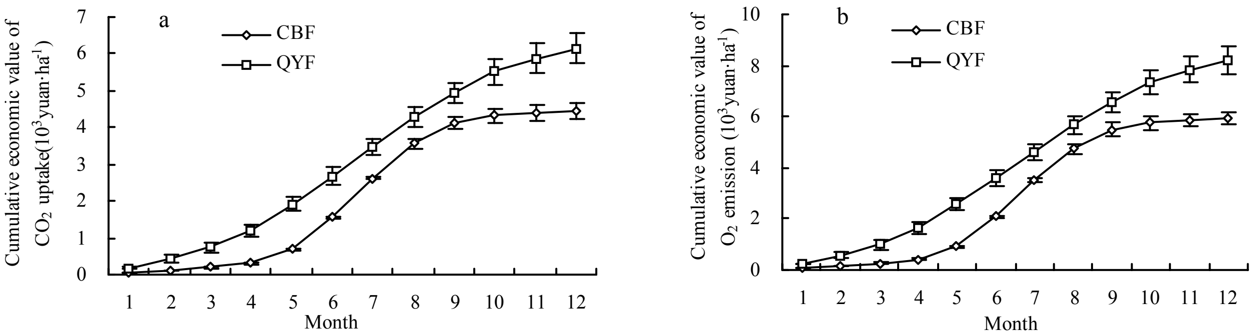

Fig. 2 Cumulative process of economic value of CO_2 uptake (a) and O_2 emission (b) by vegetation

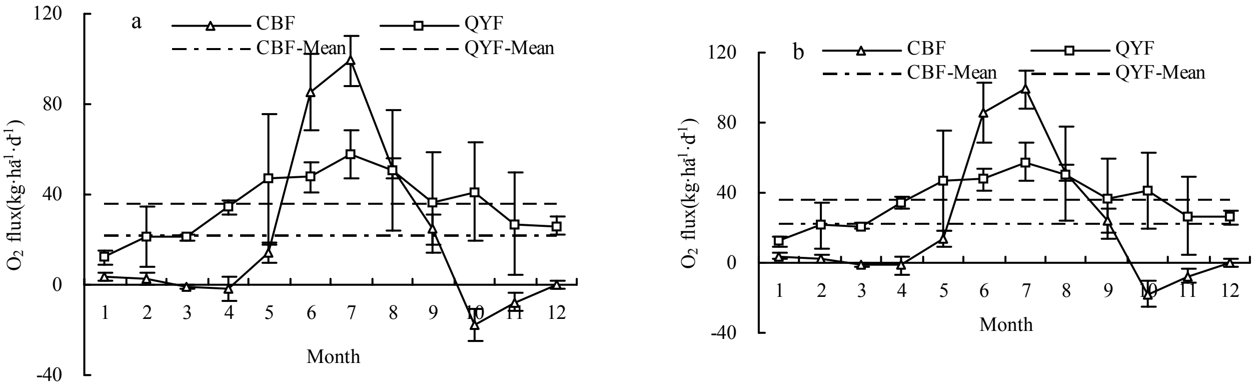

Fig. 3 Net ecosystem CO_2 uptake (a) and O_2 emission (b) fluxes

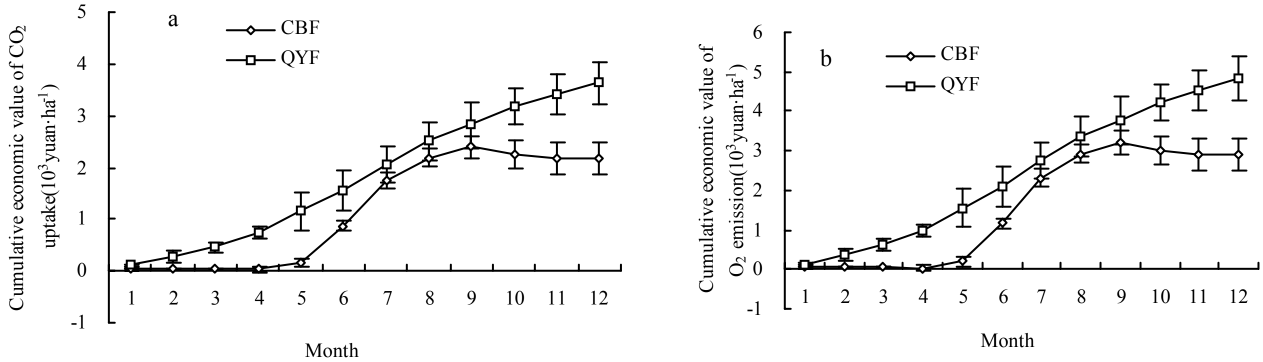

Fig. 4 Cumulative process of economic value of net CO_2 uptake (a) and net O_2 emission (b) by ecosystem

There was significant difference in cumulative process of economic value of net ecosystem gas regulation between the QYF and CBF (Fig. 4). The cumulative curves of net ecosystem gas regulation service for QYF presented sigmoid type curve,

while that for QYF followed a unimodal shape. The annual economic value of CO_2 uptake and O_2 emission was 8470.52 yuan·ha^{-1} for QYF, which was 1.66 times as large as that of CBF. Xiao et al. (2005b) reported that the value of O_2 emission for subtropical rice paddy ecosystem ranged from 9549 to 12277 yuan·ha^{-1}, which is much larger than that of QYF and CBF, and we supposed that it was attributed to higher productivity of rice paddy ecosystem. Between May and October, the cumulative economic value of net ecosystem gas regulation of QYF and CBF accounted for 66.96% and 108.70% of the annual total value. The economic value of net ecosystem gas regulation for CBF reached maximum in September, 5602.91 yuan· ha^{-1}, but in October and November CBF became a CO_2 source and O_2 sink, which brought about negative economic value and decreased the cumulative economic value.

Conclusions

There were significant seasonal variation of vegetation gas regulation fluxes for QYF and CBF, and the dynamic curves of vegetation gas regulation fluxes for QYF and CBF presented unimodal shapes. Annual economic value of vegetation gas regulation for QYF and CBF was RMB 14342.69 yuan·ha^{-1} and 10384.18 yuan·ha^{-1}, respectively, and their cumulative dynamics followed sigmoid type curve. The seasonal variation of net ecosystem gas regulation service fluxes for QYF and CBF was also significant. In terms of monthly net ecosystem gas regulation service, QYF served as a CO_2 sink and O_2 source for a whole year, while CBF served as a CO_2 sink and O_2 source for eight months. The cumulative dynamics of economic value of net ecosystem gas regulation appeared sigmoid curve for QYF and unimodal curve for CBF. Annual economic value of net ecosystem gas regulation was 8470.52 yuan·ha^{-1} and 5091.98 yuan·ha^{-1}, respectively.

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